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Fast cooling of antiproton and radioactive ion beams in future storage rings at GSI

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Abstract

Key issues of the new accelerator facility proposed for GSI are production, fast cooling, and accumulation of intense secondary beams, antiprotons and rare isotopes (RI). Single primary bunches of 2×10^{13} protons at 29 GeV and 1×10^{12} U^{28+}-ions at 1 GeV/u shall be delivered from the new, fast-ramped 100 Tm-synchrotron SIS100. A large acceptance, reversible polarity collector ring is foreseen for fast RF debunching followed by fast stochastic pre-cooling in all phase planes. The envisaged total pre-cooling times are 4–5 s for antiprotons at 3 GeV and 0.5–1 s for fully stripped RI at 740 MeV/u. A separate accumulator ring RESR is provided for stochastic accumulation of antiprotons. The RI beams are transferred to a new experimental storage Ring NESR, where electron cooling (EC) is applied simultaneously to internal target and electron–ion collision experiments. For experiments with antiprotons, a special 50 Tm storage ring HESR shall be equipped with internal target and EC up to 15 GeV, optionally also with stochastic beam halo cooling. A maximum luminosity of $2 \times 10^{32}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$ and an energy resolution of about 100 keV at lower luminosity are main objectives of the HESR concept. Basic issues for the design of the storage ring complex are discussed.

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Keywords: Storage ring; Beam cooling; Radioactive beams

1. Scientific objectives and layout of the new facility

The conceptual design report for an "International Accelerator Facility for Beams of Ions and Antiprotons" [1] on the GSI site was presented in autumn 2001. Meanwhile, GSI got 'green light' for the preparation of the 675 M€ project a quarter of which has to be contributed by international partners.

The proposed accelerator complex (see Fig. 1) is characterized by following major scientific objectives:

- Nuclear structure physics with rare isotope beams (RI beams) at high mean intensities for external target experiments and high peak

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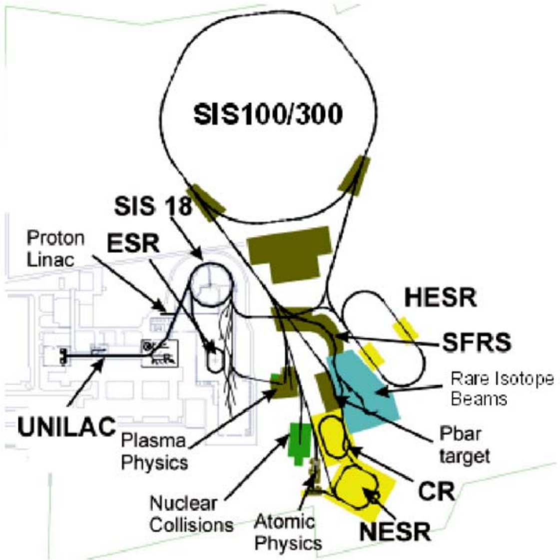

Fig. 1. Preliminary layout of the proposed accelerator/storage ring facility at GSI (see text below).

intensities for internal target experiments with cooled beams of short-lived nuclei.

- Nuclear collision experiments investigating compressed baryonic matter with heavy projectiles up to $^{238}U^{92+}$ at high specific projectile energies up to 34 GeV/u.
- Internal target experiments with cooled antiproton beams at energies up to 14.5 GeV and at luminosities up to $2\times10^{32}\,cm^{-2}\,s^{-1}$ for the investigation of exotic hadronic states with high resolution.
- Atomic physics experiments with high-Z ions in a wide energy range up to relativistic energies.
- Plasma physics experiments investigating evolution and properties of hot, dense plasmas generated by intense heavy ion beam pulses.

The layout of the proposed accelerator/storage ring complex is shown in Fig. 1. The existing UNILAC-SIS18 accelerators, supplemented by a 50 MeV proton linac, will serve as injectors. The 100 Tm-synchrotron SIS100 [2], equipped with fast-cycling, superferric[1] 2 T-dipoles (ramp rate 4 T/s), will accelerate 1×10^{12} U^{28+}-ions per cycle for RI production at 1.5–2.7 GeV/u and 2×10^{13} protons per cycle for antiproton production at 29 GeV. The high beam intensities per SIS100 cycle are obtained by means of multi-turn filling the SIS18 up to the space charge limit at injection energy (11.5 MeV/u for heavy ions and 50 MeV for protons) and by accumulating 4–5 SIS18 cycles in the correspondingly larger SIS100 ring. The superconducting 300 Tm-synchrotron SIS300, installed in the same ring tunnel, will be used to accelerate about 1×10^{10} U^{92+}-ions up to 34 GeV/u for nuclear collision experiments, but alternatively also as stretcher for SIS100-beams.

This contribution describes mainly collection, fast cooling and accumulation of RI and antiproton beams in the 13 Tm-Collector Ring (CR) complex consisting of a large acceptance CR and an accumulator ring RESR. The pre-cooled beams are transferred to two experimental storage rings, the RI beams to the 13 Tm-NESR and the antiproton beams via SIS100 to the 50 Tm-HESR. Both rings are equipped with internal experiments and electron coolers.

2. Secondary beam production

2.1. Rare isotope beams

Experiments at the existing fragments separator FRS behind SIS18 confirmed that optimal yields of unstable, neutron-rich nuclei are obtained by induced fission of ^{238}U-projectiles at kinetic energies up to 1.5 GeV/u. Therefore, ^{238}U may be considered as primary reference particle for the formation of rare, neutron-rich isotope beams at the proposed facility, which includes also a new large acceptance fragment separator Super-FRS (see Fig. 2).

The acceleration of $^{238}U^{28+}$ ions in the proposed SIS18-SIS100 accelerator combination will not only allow to attain a high primary beam intensity of 1×10^{12} ions per cycle, but will also make it possible to compress all projectiles into a single bunch of only 50 ns duration and 2% full momentum spread. Due to the strong time focusing, the increase of the longitudinal emittance

[1] The magnetic field of superferric magnets is determined by the geometry of the “warm” iron, though coils are superconducting.

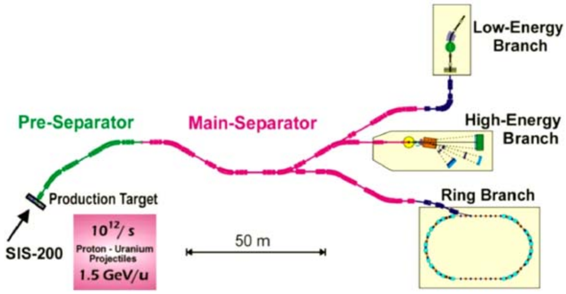

Fig. 2. Layout of the Super-FRS [3], a magnetic separator equipped with superferric dipole and quadrupole magnets. The maximum bending power $B \times \rho_{max}$ is 20 Tm, the resolving power $M/\Delta M$ about 1500.

of the secondary beams is minimized. In addition, after injection of the secondary beam bunch to the CR, the momentum spread, $\delta p/p$, can be reduced by bunch rotation in a large FRF-bucket within a few milliseconds by a factor of up to five.

It should be mentioned that, by each beam bunch, a rather large fraction (up to 30%) of the total beam energy of about 57 kJ at 1.5 GeV/u is deposited in a small volume of about 10 mm^3 in the (C, Al or Mg) production target of a few g cm^{-2} thickness. The power loss of 340 GW averaged over 50 ns will destroy every kind of conventional (solid) target by shock waves, immediate melting and even evaporation [4]. Therefore, the development of targets that can be renewed after every passage of a beam bunch, i.e. within 500 ms, is crucial.

2.2. Antiproton beam

The bunching procedure described above is applied also to the proton beam for the antiproton production. The concept—kinetic energy of 29 GeV and intensity of 2×10^{13} primary protons, target and collection techniques, and acceptance of the CR (see Table 2)—is very similar to that of the former AAC-complex at CERN [5, 6]. However, because of the higher proton intensity and energy, we expect a somewhat higher antiproton yield of 5×10^{-6} per incident proton at the desired energy of 3 GeV, i.e. about 1×10^8 per bunch.

3. Fast cooling in the CR complex

The necessity of fast cooling and accumulation in the CR complex is determined by the consumption rates at the highest luminosities for the internal target experiments with the cooled secondary beams and, in the case of rare isotope beams, additionally by the decay time $\gamma\, \tau_{1/2}$ of the exotic nuclei in the laboratory system (see Table 1).

3.1. Structure of the CR

The large acceptance CR (see Table 2 and Fig. 3) is the first stage of the storage ring branch of the proposed facility [7]. Its maximum bending power of 13 Tm allows for the injection of rare isotope beams at 740 MeV/u and, with reversed polarity of all magnets, of antiproton beams at 3 GeV.

Mainly due to the different particle velocities the ion optics of the CR has to be flexible in order to achieve optimal conditions for fast stochastic cooling for both species of beams (see Table 2). In addition, for time-of-flight mass spectrometry of exotic nuclei, the ring has to be operated in the isochronous mode at $\gamma = \gamma_t \approx 1.84$, where γ and γ_t are the relativistic Lorentz factor and the transition point, respectively. In this mode, the

Table 1
A few examples of expected RI intensities per SIS100 cycle after Super-FRS and injection to the CR

Nucleus	Yield/cycle	Decay time $\tau_{1/2}$ (s)
$^{11}Be^{4+}$	6.0×10^8	13.8
$^{46}Ar^{18+}$	3.2×10^8	7.8
$^{55}Ni^{28+}$	3.9×10^7	0.2
$^{71}Ni^{28+}$	6.7×10^6	2.6
$^{91}Kr^{36+}$	4.2×10^7	8.6
$^{104}Sn^{50+}$	5.0×10^5	20.8
$^{132}Sn^{50+}$	4.0×10^7	39.7
$^{133}Sn^{50+}$	4.0×10^6	1.4
$^{187}Pb^{82+}$	1.0×10^7	15.0
$^{207}Fr^{87+}$	3.2×10^7	14.8
$^{227}U^{92+}$	1.6×10^6	66

The heavy species are produced by induced fission of 1×10^{12} uranium projectiles per cycle at 1.5 GeV/u, the lighter ones by fragmentation of lighter projectiles, e.g. ^{55}Ni from ^{58}Ni, at lower specific energies. Decay times are given for nuclei at rest [3].

Table 2
Selection of basic CR parameters

Bending power	13 Tm		
Circumference	200 6 m		
Super periodicity	2		
Lattice type	FODO		
Operation modes	pbar cooling	RIB cooling	Isochronous mode
Max. energy (GeV/u)	3	0.79	0.79
Betatron tunes Q_h	4.62	3.42	2.36
Q_v	4.19	3.36	3.36
Transition energy, γ_{tr}	4.3	2.88	1.84
Horizontal acceptance (μm)	240	200	70
Vertical acceptance (μm)	240	200	50
Momentum acceptance	$\pm$3%	$\pm$1.75%	$\pm$0.7%
St. cooling at (GeV/u)	3	0.74	—
at $\beta = v/c$	0.97	0.84	—
at γ	4.2	1.8	1.84
Revolution frequency (MHz)	1.5	1.3	1.3
Frequency slip factor η	$\leqslant$0.07	0.17	0.0
RF peak amplitude (kV)	400	400	—
$\delta p/p$ after debunching (95%)	$\pm$0.6%	$\pm$0.35%	—

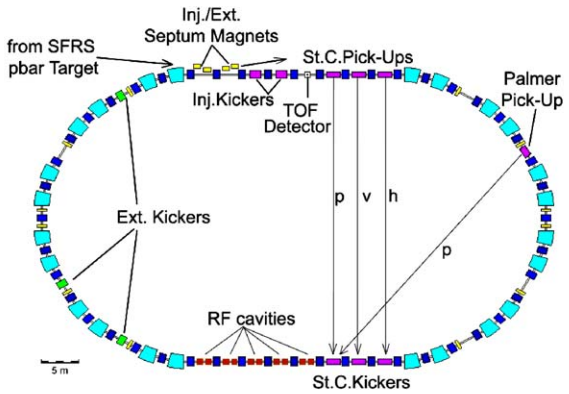

Fig. 3. Layout of the CR. The ring will be equipped with superferric dipole magnets. The Palmer pickup is necessary only for rare isotope beams at the beginning of momentum cooling (too strong unwanted mixing). Cooling branches: p means momentum cooling, v vertical emittance cooling and h horizontal emittance cooling.

revolution periods of single beam particles are measured turn by turn. The spectrum of periods reflects the different mass-to-charge ratios of circulating nuclei.

So far, two different lattice structures were studied carefully: a lattice with identical ion optical settings in 180°-arcs and a so-called split ring lattice with strongly reduced frequency slip factor η in the arc between stochastic cooling pickups and kickers. This lattice concept had been proposed already about 10 years ago for the Super-LEAR lattice [8]. The results of the studies for the split ring lattice in comparison with the symmetric lattice may be summarized as following:

- the number of quadrupole families is increased by nearly a factor of two,
- chromaticity and higher order field corrections are much more complicated, and
- the dynamic apertures seem to be considerably smaller.

For the final choice of the CR lattice numerical calculations of transverse cooling rates for all phases of the cooling process have to be completed.

3.2. Bunch rotation

As explained above the injected secondary beam particles are concentrated in a single, 50 ns long beam bunch. This permits—immediately after injection—fast $\delta p/p$ reduction by a factor of approximately 5 by means of bunch rotation followed by adiabatic debunching.

The first harmonic RF cavities (see Fig. 4 and Table 3) have to be tuned to 1.3 MHz for RI beams and to 1.5 MHz for antiprotons. A rather high total RF voltage of 400 kV_{pp} is necessary in the case of RI bunches, for which a compromise between sufficiently large horizontal acceptance of the storage ring and sufficiently small frequency slip factor η was much harder to find. With the chosen ion optics for RIB cooling (see Table 2) $\eta \approx 0.17$ was achieved, which still requires the high RF voltage mentioned before.

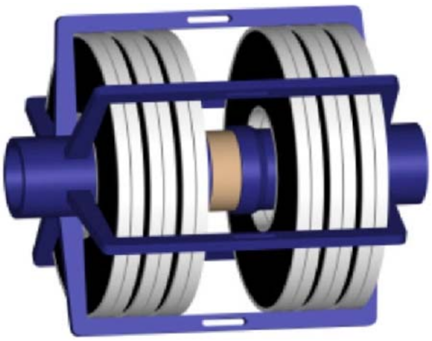

Fig. 4. : Preliminary layout and parameters of the CR bunch rotation cavity. 10 cavities are required.

Table 3
Preliminary parameters of the bunch rotation cavity for the CR

Load material	Metallic alloy (MA)
Resonant RF for RI	1.3 MHz
Resonant RF for pbar	1.5 MHz
Voltage	40 kV_{pp}
Shunt impedance	929 Ω
RF Power	862 kW
Length	1 m

3.3. Stochastic cooling

The starting conditions for stochastic cooling are determined by large transverse emittances and by the momentum spread after bunch rotation and adiabatic de-bunching (see Table 4). Because of the stronger (unwanted) mixing the momentum cooling of rare isotope beams starts with the so-called Palmer method until $\delta p/p$ is below the mixing limit for notch filter cooling ($\delta p/p \approx \pm 0.1\%$).

The Palmer pickup (see Fig. 3) is installed at a position, where the dispersion amplitude is large compared to the betatron amplitude. The momentum deviation is deduced from the difference between signals from inner and outer electrodes of the pickup system. As the Schottky power is proportional to the square of the ionic charge number Z, the high charge states of rare isotopes ($Z \geqslant 25$) guarantee an excellent signal to (thermal) noise ratio.

Transverse cooling of antiprotons and rare isotopes will be switched on when the unwanted mixing between pickups and kickers has reached

Table 4
Beam parameters and cooling times at CR (95%—values at corresponding particle energies)

		Pbar cooling	RI cooling
After injection	Horizontal emittance (μm)	240	200
	Vertical emittance (μm)	240	200
	Momentum spread (%)	±3	±1.75
After debunching	Horizontal emittance (μm)	240	200
	Vertical emittance (μm)	240	200
	Momentum spread (%)	±0.5	±0.35
After cooling	Horizontal emittance (μm)	0.5	5
	Vertical emittance [μm]	0.5	5
	Momentum spread [%]	±0.1	±0.05
Total cooling time (s)		5.0	0.5–1

tolerable values and the wanted mixing between kickers and pickups is still strong enough. This is the case at $\delta p/p \approx \pm 0.3\%$. This preliminary estimate has to be confirmed by numerical simulation of the cooling process. The corresponding computer code based on the Fokker–Planck approach is in preparation and should be available by the end of this year.

The preliminary technical layout of the stochastic cooling system at the CR is based on power-amplifiers for two or three bands in the frequency range 1–4 GHz. The 50 Ω-kickers will be equipped with a total power of about 8 kW (CW, at 1 dB compression). Mainly for the antiproton cooling it is crucial to aim at optimal signal to noise ratio at the pickup side. Cooling of pickup terminators with liquid-N_2 and application of low noise head amplifiers are envisaged. In addition, the mechanical distance between pickup electrodes is planned to be reduced synchronously to the progress of transverse cooling, in order to yield an optimal Schottky signal.

The requirement of a total cooling time of 5 s for antiprotons is considered to be feasible if the "state of the art" achieved at CERN and FNAL is applied adequately to the technical design of the CR cooling system. For rare isotope cooling, the total cooling time of 0.5 s seems to be rather challenging, though the signal to noise ratio for highly charged ions is excellent. Fortunately, the results of cooling experiments at the ESR with artificially heated fully stripped uranium ions at 410 MeV/u are quite promising (see Fig. 5). Cooling time constants of less than 1 s for momentum cooling and 2 s for horizontal emittance cooling were obtained with about 500 W total power at 50 Ω-kickers in the frequency band 0.9–1.65 GHz.

So far, we believe that the same pickup and kicker electrodes can be employed for both the RI and the antiproton stochastic cooling. Novel planar electrodes (slit couplers) suitable for the relativistic parameter γ of the beam particles, 1.8 for RI and 4.2 for antiprotons, are under development. The 15% difference in the particle velocities has to be taken into account for the signal combination as well as for the electrical length adjustment of transmission lines and notch filters. Suitable electronically switched delay units are under development.

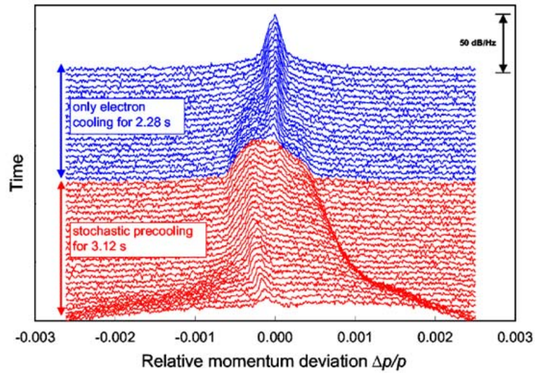

Fig. 5. Stochastic momentum cooling of an artificially heated $^{238}U^{92+}$ beam at 400 MeV/u in the ESR. It is seen that a cooling time constant of about 1 s is attained. Schottky traces recorded every 125 ms start at the bottom.

4. Beam accumulation

4.1. Rare isotope accumulation

Pre-cooled rare isotope bunches can be transferred either directly or after deceleration in the RESR to a lower specific energy to the NESR. If allowed by the lifetime of nuclei, the rare isotope beams may be accumulated in the NESR by means of RF stacking and electron cooling. This method has been applied successfully for many years at the existing ESR. Achievable stacking factors are proportional to the beam lifetime divided by the time between two subsequent injections. If the latter is assumed to be about 1 s, we may expect stacking factors that are approximately equal to the nuclear decay time of the exotic ions in the laboratory system (see table 1). Hence, e.g. for ^{132}Sn, one could accumulate up to 3×10^9 nuclei within 70 s. With an internal target of 4×10^{13} atoms/cm^2 and an ion revolution frequency of ≈ 1 MHz of ions a luminosity of approximately 1×10^{29} cm^{-2}s^{-1} would be available for experiments.

4.2. Antiproton accumulation

After pre-cooling in the CR, single bunches of up to 1×10^8 antiprotons are transferred every 5 s to the accumulator ring RESR, where RF stacking will be combined with stochastic accumulation.

The injected bunch is captured into a first harmonic RF bucket, moved towards the tail of the stack and de-bunched there. The momentum cooling into the stack core is made by two or three separate pickup and kicker systems. In addition, the core of the stack has to be cooled all the time in all phase planes. About 7×10^{10} antiprotons per hour shall be accumulated this way. The accumulated antiproton beam is transferred to SIS100 for further acceleration to the energy required for the internal target experiment at the HESR. The design of the RESR, recently added to the storage ring complex, is in a very early stage. The main motivation was, to have a ring especially optimized for the fast accumulation of antiprotons. The lattice is under investigation and the conceptual design of the stochastic accumulation system has just begun. We hope to get, at least, some advice from experts at FNAL and CERN, where similar requirements have been fulfilled many years ago.

5. Electron cooling concept

5.1. Ri beams in NESR

Because of the short lifetime of exotic nuclei one has to optimize stochastic pre-cooling in the CR and final electron cooling in the NESR. Stochastic cooling rates decrease strongly when the beam temperatures approach a certain lower limit, where the (wanted) mixing is so slow and the signal to noise ratio so small that the cooling process is stopped. Electron cooling rates show the opposite behaviour. They reach optimal values as soon as the longitudinal and transverse beam temperatures are small enough, i.e. the relative velocities between cooling electrons and ions are comparable to the mean electron velocity spread. The envisaged final beam parameters after pre-cooling in the CR may be considered as optimal parameters for the subsequent electron cooling in the NESR, where electron cooling rates of 1–10 s^{-1} are required.

Main applications for electron cooling at the NESR are fast accumulation of RI beams, compensation for beam heating and mean energy loss in the internal target in proton scattering experiments, and formation of short ion bunches for the collision with electron bunches for electron scattering experiments, including the compensation for phase space dilution by beam–beam effects.

Design characteristics of the electron cooling device for the NESR are:

- variable electron energy in the range 10–450 keV corresponding to electron cooling in the ion energy range 20–800 MeV/u,
- electron current of up to 2 A at a beam diameter of 25 mm,
- low transverse electron temperature $kT_{e,\perp} \leqslant$ 0.2 eV,
- solenoid field in the cooling section of about 0.2 T with a straightness of $|B_\perp/B_{||}| \leqslant 5 \times 10^{-5}$ ($B_\perp$, $B_{||}$ are transverse and longitudinal field components), and
- effective cooler length of 4 m.

The rather tight tolerance for the straightness of the magnetic field in the cooling section is necessary to attain the envisaged cooling rates $\geqslant 10\,s^{-1}$, especially at high beam energies. Numerical simulations using different codes have confirmed this precondition. Another result of the simulations is the necessity of sufficiently high magnetic field strength, in order to achieve the so-called magnetized cooling delivering much higher cooling rates compared to non-magnetized cooling at lower fields. The simulation results are in fairly good agreement with experimental cooling results at the ESR in a wide range of ion energies up to 450 MeV/u.

5.2. Antiprotons in HESR

Very similar to the situation in the NESR, beam quality and luminosity in the HESR will be determined by the capability to counteract beam heating caused by antiproton–target interactions and by intra-beam scattering. The realization of the technical requirements that can be derived from the experimental experience with electron cooling at lower energies is quite challenging. Strong cooling can be achieved only with magnetized cooling in a strong longitudinal magnetic field, $B_{||} \geqslant 0.5\,\mathrm{T}$, along the cooling section of about 30 m length. The requirements concerning very small transverse magnetic field components, e.g. $|B_{\perp}/B_{||}| \leqslant 1 \times 10^{-5}$, are even more stringent than for the NESR electron cooler and absolutely mandatory for attaining cooling rates of 0.1–$0.01\,\mathrm{s}^{-1}$ at kinetic antiproton energies up to 14.5 GeV.

The generation of a 'cold' electron beam ($\mathrm{k}T_{\mathrm{e},\perp} \leqslant 0.2\,\mathrm{eV}$, $\mathrm{k}T_{\mathrm{e},||} \leqslant 0.1\,\mathrm{meV}$) at energies up to 8 MeV—corresponding to 14.5 GeV antiproton energy—with an electron current of up to 1 A is another technical challenge. If magnetized cooling is required, two possible solutions for electron acceleration are conceivable: electrostatic acceleration or linear RF accelerator. Compared to the acceleration by an RF linac, electrostatic acceleration has the advantage of small energy spread in the electron beam. Moreover, it provides continuous cooling without any time structure, which would be appropriate for the cooling of a coasting antiproton beam in the HESR.

The acceleration and recuperation of electron beams in commercially available electrostatic accelerators might be feasible if the electron current loss is below 100 μA. First experiments in the framework of a similar research and development program at FNAL/USA are promising [9], but, so far, the FNAL-project is not focused on the higher cooling rates by means of magnetized cooling. The technical feasibility of an electron cooling device for the full energy range of the HESR is presently being studied in cooperation with BINP/Novosibirsk [10].

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